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SYSTEMS APPROACH TO THE CONCEPT OF ENVIRONMENT[1, 2]

BERNARD C. PATTEN, Department of Zoology and Institute of Ecology, University of Georgia, Athens, GA 30602

Abstract. A systems theory of environment formulates causal interactions between things, including organisms, and their environments in terms of four system theoretical abstract objects. *Creaons* receive stimuli and implicitly create input environments. *Genons* react to received causes and generate potential output environments as effects. A *holon* represents the combined input-output model of an entity consisting of a creaon and a genon. An *environ* is a creaon and its corresponding input environment, or a genon and its related output environment. The theory is presented in terms of three propositions that: (1) recognize two distinct environments (input and output) associated with things, (2) establish things and their environments as units (environs) to be taken together, and (3) partition systems into input and output environs associated with intrasystem creaons and genons, respectively.

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Ecology is the biological science of environment. It considers environment as a derivative of physiology in the sense that environment contains resources to be mobilized by organisms, and conditions of life under which this mobilization must occur. The resource in least supply at any given time is rate limiting (law of the minimum), as is the factor, such as temperature, in greatest extreme (law of tolerance). Thus, the organism is seen by ecology to inhabit a physiological life space bounded by conservative and nonconservative elements of its environment —resources and factors, respectively.

The nature and composition of this life space varies according to the character of the larger system of which the organism is seen as a part. Population aspects of environment encompass the intraspecific reproductive, genetic, demographic and social worlds of the organism. A community aspect refers to interspecific biotic associations. The ecosystem aspect takes into account all features of the organism's biotic and abiotic interactions.

Although the strict ecological idea of environment is based on the individual organism, loose usage frequently extends the concept from individuals to groups (*our* environment), or suggests something absolute (*the* environment). The dictionary defines environment variously as: "the surrounding conditions, influences or forces that influence or modify; the whole complex of climatic, edaphic and biotic factors that act upon an organism or an ecological community and ultimately determine its form and survival; the aggregate of social and cultural conditions that influence the life of an individual or community," (Merriam-Webster 1971). The significant features of environment in ordinary usage are that some defined subject (individual or group) is immersed in or surrounded by it, and influenced by it through a causal relationship. This causality, as developed below, is the basis for the present attempt to express environment in terms of system theory, which is the purpose of this paper.

SYSTEMS DEFINITIONS

Systems ecology is a branch of ecology that applies systems thinking and methods to ecological problems. Several definitions of basic system concepts are useful in prospect of a systems approach to defining environment. A system is a partially interconnected (interacting or causally joined) set of components. Interactions may be mediated by energy-

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matter through transactions, or by information through communications. Transactions and communications correspond, respectively, to transfers of conservative resources and nonconservative factors in the physiological account of environment described above.

In a hierarchical model of nature, any given system can usefully be abstracted as three discrete levels separated out of a hierarchical continuum: system, subsystem and supersystem. Subsystems are components of the systems. Supersystems are composed of systems. Koestler's (1967) term "holon" for a hierarchical system can be used to refer to any of these three levels of organization, according to the frame of reference.

A system is closed if it does not interact with another system, and open if it receives causes from or generates effects to another system. A system boundary provides the interface with other systems and is defined by specifying its component set. Input is any movement of energy-matter or information from supersystem to system, and output is any similar movement across the system boundary in the opposite direction.

ECOLOGICAL CONCEPTS OF ENVIRONMENT

Environment as a concept has not been treated very seriously in ecological literature and only a few explicit works are available. Mason and Langenheim (1957) defined *environmental phenomena* as those that have or may have an operational relation with any organism. The *environmental relation* of an organism is the sum of empirical relations between the environmental phenomena and any individual organism. The *operational environment* of an organism consists of those instantaneous environmental phenomena that actually enter a relation with an organism; the concept applies to specific individual organisms. Space and time frames of the operational environment are determined by the organism. The life span of the organism corresponds to the existence time of its operational environment. *Potential environment* consists of the set of environmental phenomena that may enter into an environmental relation at some point in the ontogeny of an organism. *Non-environment* consists of all phenomena (indirect, historical and organism-caused) which never enter into a direct environmental relation with the organism.

Mason and Langenheim (1957) asserted, "the environment of any organism is the class . . . of those phenomena that enter a reaction system of the organism or otherwise directly impinge upon it to affect its mode of life at any time throughout its life cycle as ordered by the demands of the ontogeny of the organism or as ordered by any other condition . . . that alters its environmental demands." Only direct factors were considered part of environment. "[Indirect and historical] factors both function to condition a phenomenon . . . to which an organism then reacts. Important as this is to the ecosystem the only [organism] reaction . . . is to an already conditioned phenomenon. The state of the phenomenon prior to its conditioning is outside the scope of operational . . . and . . . potential environment. . . . This may seem to rest upon trivial distinctions, but we are convinced that this is the precise boundary between clarity and confusion in the problems of the environment."

Thus, chains and networks of historical causation, which condition direct factors, are excluded from Mason and Langenheim's (1957) concept of environment: ". . . we must reject the implication that . . . [causal] chains constitute a unitary event playing a significant role in the environmental relation even though the steps are very important to the ecosystem. . . . There is also a philosophical reason for removing indirect factors from the concept of environment. To introduce indirect factors into causal relations within the environment is to introduce an infinite regress into the system of explanation. Every cause has in turn itself a cause which becomes an indirect cause of the most recent effect. The regress is toward the limbo of ultimate cause along an infinitely reticulating path; for this we have neither finite description nor finite explanation. . . . To include such relations in environment is to confuse environment with its history."

A systems ecology concept of environment must take issue with the Mason and

Langenehim theory. The whole thrust of a systems understanding of nature is to reconstruct the main patterns of causation in models. Within the confines of a finite model forming a whole from interconnected parts, an expanded concept of environment of the parts is possible, which includes both direct and indirect factors. The intrasystem causal network is never an unknown infinite regress, but is explicit to the model boundary which constitutes the limit of finite description and explanation which were lacking in Mason and Langenheim's time. While the conditioning of direct causes by indirect effects may be temporally antecedent, ecosystems and their models are persistent or recurrent organizations so that historical patterns of causation are relevant, with perhaps small corrections for evolution, to present and future patterns as well.

Such a systems view of environment has precedent in an ecological work by Haskell (1940), who focused on events in the universe that may eventually influence an organism during its lifetime. Their influence is limited by how fast causality can be propagated, no faster ultimately than the speed of light. Thus, corresponding to each instant in the life of an organism is a light cone. (Haskell 1940, fig. 1) bounding the spatiotemporal extent of possible causes. The cones diminish in time as the universe that can possibly affect the ageing organism contracts: "The cones prepresent . . . a steadily shrinking region . . . within which the fastest moving process—light, traveling at about 300,000 km a second—can start, at any point-instant . . . during the organism's existence, and effect (sic) it before its end. . . . This region is equal to a geometric hyperbody, defined below as 'habitat', and, constitutes part of 'environment.' Habitat is the "immediate environment" (Haskell 1940, p. 7), taken as Weaver and Clements (1929) defined it: "Every part of the environment that exerts directly or otherwise [i.e., indirectly] a specific influence upon the life of the plant is a factor of the habitat."

Thus, Haskell's concept of environment includes not only the direct causes of Mason and Langenheim, but indirect causes as well, so long as their eventual influences can be propagated to a subject, such as an organism, during its existence interval. Systems ecology models that represent complex intrasystem webs of direct and indirect causation make it possible to implement such an expanded concept of environment. A formal approach to such implementation is described below.

HOLONS

General systems theory defines a system to be a partially interconnected set of objects, then proceeds to describe the objects and various aspects of their interactive coupling. Formal details differ with the specific theory, but most general systems objects have in common that in some sense they perform a double mapping of time into state, then state into output. Examples are "finite state machines" of Gill (1962), "abstract objects" of Zadeh and Desoer (1963), Wymore's (1967) "formal systems," the "general systems" of Klir (1969) given according to five definitions, "T-processors" of Windeknecht (1971), and "general time systems" of Mesarovic and Takahara (1975). All such units may be made causal, and can be generalized under the nonspecific hierarchical object, *holon* (Koestler 1967). An extensive theory of the causal holon as the basis for a systems concept of environment has been presented elsewhere (Patten *et al* 1976), based on Zadeh's model (Zadeh and Desoer 1963, Zadeh 1969). This theory is outlined below, with notation modified according to Mesarovic and Takahara (1975).

To model a causal link between two entities requires some kind of process or object whose action converts cause to effect. Such an object, H, is a relation on attributes, $\forall\epsilon \mathrm{A}$, that are time functions in a time domain, T. For each $a\epsilon\mathrm{A}$ a is a behavior $\forall t\epsilon\mathrm{T}$, $a(t)$ is the value of a at time $t\epsilon\mathrm{T}$, a^t is the segment of a prior to t, and a_t is the behavior segment of a beginning at and following t. This object definition provides latitude in selecting the set A of behavioral attributes.

The holon becomes oriented when its set of attributes is partitioned into inputs, Z, and outputs, Y. The relation H on

A is then expressed as a set of input-output time segments: $(z,y)\epsilon H$, $z\epsilon Z$ and $y\epsilon Y$. The oriented holon associates response (output) time sequences with stimulus (input) histories. In developing the holon as a causal object, given output sequences must be uniquely associated with given input segments. This property is incorporated in the notion of a functional holon, where H is construed as a map (function) of inputs, z, into outputs, y. Such an object is said to be *determinate*, i.e., a time series of inputs from its environment uniquely determines a corresponding time series of outputs.

Dynamic behavior of a determinate object occurs in response to the object's environment's behavior, which is received as input. This is modeled by introducing a third set, X, of object variables, states. Heuristically, inputs $z\epsilon Z$ serve to map time $t\epsilon T$ into states $x\epsilon X$, and the states take inputs $z\epsilon Z$ into outputs $y\epsilon Y$. States are generated by a state transition function:

$$\phi: Z \times X \rightarrow X,$$

and outputs are generated by a response function:

$$\rho Z \times X \rightarrow Y.$$

The only other requirement for a determinate holon to be causal is that it not respond at time t to inputs received after t. That is, the object cannot anticipate its future environment; it is *nonanticipatory*. If a determinate object were to generate more than one output sequence corresponding to a given input sequence, the only way it could do this (since it is determinate) would be based on information about the future. This possibility is precluded for the causal object.

The full theory (Patten *et al* 1976) should be consulted for details. The causal holon may serve at either the system or subsystem level. The focus of the original work was on intrasystem propagation of causes between subsystem level holons. As a result, consequences of the theory for a system concept of environment were not as clearly perceived as they are now. Environment is normally a supersystem level concept. Causation was considered to be introduced as inputs from an environment at the supersystem/system interface, then propagated through the interactive network connecting subsystem holons, and finally dissipated as output effects generated to the environment across the system boundary. The key to recognizing the main features of the theory and its implications for an improved concept of environment lay in focusing on intrasystem environments associated with subsystem level holons. These environments may be explicitly identified and measured as a causal reticulum within a system model, with consequences that emerge as three main points of the theory. These points are developed as specific propositions in the next three sections.

FIRST PROPOSITION

Proposition 1: Every object H defines two environments: an input environment H', *and an output enviroment* H''. *The prerogative of environment definition is that of the object.*

The causal model of subject/environment interaction leads to not one, but two equally plausible and useful concepts of environment. The first is *input environment* H', defined by holon H in the act of receiving energy-matter or perceiving information. Behavioral attributes of the real world that do not impact H as input during its existence interval cannot influence the state of the object. They go unrecorded by H and consequently are not part of its environment. So basic is this environment defining function that this aspect of the holon is given (Patten *et al* 1976) a special name, *creaon*, to signify an implicit act of environment creation. Mason and Langenheim (1957) restrict the concept of (input) environment to phenomena that "directly impinge" upon the organism, whereas Haskell (1940) includes, in addition, the indirect causes from which direct ones are generated. The latter, and the present approach, are more consistent with a systems view, and in the context of finite ecosystem models do not produce the infinite causal regress to which Mason and Langenheim objected. That is, when H is a subsystem level component, H' is traceable only to the model boundary, becoming beyond this merely undifferentiated input to the system level. The within system portion of H' is thus explicit in the concept of input environment.

Reciprocally, the second concept of environment is that of an *output environment* H''. This begins as a set of potential environments embodied in the states of H. These states are converted to outputs through interaction of H with other objects (creaons). This is, to produce an actual output environment from potential environment implicit in the state structure of H requires holon production of potential attributes, then sequential creaon selections to achieve realization of these potentials. Output environment H'' is the resultant causality propagated from H as a network of direct and indirect effects. This environment generating property of holons is equally basic to the creaon function, and to distinguish it the name *genon* is given (Patten *et al* 1976). As in the creaon case, an infinite progression of effects from H is implied, but at the component level in the context of finite models, the progression terminates at the system level boundary beyond which only undifferentiated output is recognized. The within system portion of H'' is thus explicit in the concept of output environment.

Neither Haskell (1940) nor Mason and Langenheim (1957) considered output environment as a proper component of the general concept of environment. However, an older physiological theory provides explicit justification for the output environment. von Eexküll (1926) presented a picture of environment as an organism surrounder in terms of the following set of concepts:

World-as-sensed: "Every animal is a subject, which, in virtue of the structure peculiar to it, selects stimuli from the general influences of the outer world, and to these it responds in a certain way."

World-of-action: "These responses, in their turn, consist of certain effects on the outer world, and these again influence the stimuli."

Function-circle: "In this way there arises a self-contained periodic cycle, which we may call the *function-circle* of the animal. The function circles . . . connect up . . . in the most various ways, and together form the function-world of living organisms, within which plants are included. For each individual animal, however, its function-circles constitute a world by themselves, within which it leads its existence in complete isolation."

Inner world: "The sum of the stimuli affecting an animal forms a world in itself. The stimuli, considered in connection with the function circle as a whole, form certain indications which enable the animal to guide its movements. . . . The animal itself, by the very fact of exercising such direction, creates a world for itself, which I shall call the *inner world*."

Surrounding world: "World-of-action and world-as-sensed together make a comprehensive whole, which I call the *surrounding world*."

World-as-sensed and world-of-action correspond to input and output environments, respectively, and the latter is thus clearly distinguished. Moreover, von Uexküll's view of the organism/environment relation is unitary: "The entire function circle formed from inner world and surrounding world . . . constitutes a whole which is built in conformity with plan, for each part belongs to the others, and nothing is left over to chance . . . where there is a foot, there is also a path; where there is a mouth, there is also food; where there is a weapon, there is also an enemy. . . . If this circle is interrupted at any point whatsoever, the existence of the animal is imperilled. . . . continuity of the complete whole must never be lost sight of." Output and input environments are continuous through the function circles of the organism, and that continuity erases, in theory, any distinction between them. However, there is the matter of practicality to be considered: "All the [function] circles, however far they lie separated from one another in the world-as-sensed, intersect in the steering apparatus of the inner world, and then separate from one another again in the world-of-action." World-as-sensed (input environment) and world-of-action (output environment) are, for all practical purposes, separate by virtue of the enormity of reality compared to the identifiable sphere of influence of any single organism (holon).

Thus, the first proposition. Every interacting thing in nature defines two separate and distinct environments, both taken to include the network of causes and effects as far as these are traceable in any particular model in which the defining object serves as a component.

SECOND PROPOSITION

Proposition 2: The internal cause propagating structure of systems cannot be completely determined, i.e., all causal paths in the interactive network accounted for, without input or output reference to an external environment. The prerogative of realization of internal system structure is that of environment.

This proposition, developed in detail in Patten *et al* (1976), can best be presented here in terms of an example. Figure 1 illustrates a simple steady state model of marine coprophagy (Cale and Ramsay 1970, description in Patten *et al* 1976, Appendix). The model consists of four holons in series, with a feedback loop connecting H_3 and H_4. H_1 is a mud crab, *Callianassa major;* H_2 is the feces of this animal; H_3 includes all other benthic invertebrates of the marine community under consideration; and H_4 is defined as the feces of this latter group of animals. The model is simple in its interactive structure, and for that reason, quite instructive. Causality is expressed as carbon flow (gC m^{-2} y^{-1}) and system state is represented by carbon storages (gC m^{-2}).

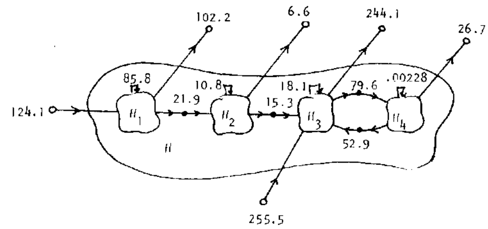

FIGURE 1. Steady state marine coprography model (Cale and Ramsay 1970). Holon inputs and outputs represent carbon flows in gC m^{-2} y^{-1}, and states represent carbon storages in gC m^{-2}.

H_1 *Callianassa major*
H_2 *C. major* feces
H_3 Benthic invertebrates
H_4 Benthic invertebrate feces
Carbon flow: x's and y's in gC m^{-2} y^{-1}
z's in gC m^{-2}

Environmental inputs are received at H_1 and H_3, and outputs from the system are generated (respiration) by all four holons. Table 1 presents the model in tabular (matrix) form.

To account for all possible holon interactions within such a model, a property

TABLE 1

Steady state marine coprography model H, *as shown in figure 1.*

H_i \ H_j (to / from)	x_1	x_2	x_3	x_4	z_{10}	z_{20}	z_{30}	z_{40}	$\underset{\sim}{z}$	$\underset{\sim}{T}$
x_1	0*	0	0	0	124.1	0	0	0	124.1	124.1
x_2	21.9	0	0	0	0	0	0	0	0	21.9
x_3	0	15.3	0	52.9	0	0	255.5	0	255.5	323.7
x_4	0	0	79.6	0	0	0	0	0	0	79.6
y_{01}	102.2	0	0	0	0	0	0	0	0	0
y_{02}	0	6.6	0	0	0	0	0	0	0	0
y_{03}	0	0	244.1	0	0	0	0	0	0	0
y_{04}	0	0	0	26.7	0	0	0	0	0	0
$\underset{\sim}{y}$	102.2	6.6	244.1	26.7	0	0	0	0		
$\underset{\sim}{T}$	124.1	21.9	323.7	79.6	0	0	0	0		

*Entries denote carbon flows in gC m^{-2} y^{-1}. The state variables for $H_1, \ldots, H_4$ are $x_1, \ldots, x_4$, respectively; z_{i0} is input from the system's input environment H' to holons H_i in rows i (i=1, . . . , 4); y_{0j} is output to the output environment H'' from holons H_j in columns j (j=1, . . . , 4). $\underset{\sim}{z}$ and $\underset{\sim}{y}$ are input and output vectors, and $\underset{\sim}{T}$ is the throughput vector. Correspondences with figure 1 are obvious.

of mathematical graphs, *transitive closure* (Ore 1962), is required. This property is illustrated for the marine coprophagy model by the set of matrices shown in table 2. Let $B=(b_{ij})$ be a binary

TABLE 2

Boolean matrices for the marine coprophagy model.†

$$B = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{bmatrix} \qquad B^2 = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 1 & 0 & 1 & 0 \\ 0 & 1 & 0 & 1 \end{bmatrix}$$

$$B^3 = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 1 \\ 1 & 0 & 1 & 0 \end{bmatrix} \qquad B^* = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 \end{bmatrix}$$

†Row and column headings are state variables $x_1, \ldots, x_4$ for holons $H_1, \ldots, H_4$. Orientation is such that column elements propagate causality to row elements.

Boolean adjacency matrix denoting direct causal coupling (paths of length one) from H_j to H_i, $i, j=1, \ldots, 4$. Performing matrix multiplication, B^2 entries identify indirect couplings via paths of length two, B^3 via paths of length three, and in general B^k via paths of length k. The table 2 matrices B, B^2 and B^3 may be readily verified by reference to figure 1.

The matrix $\sum_{k=1}^{\infty} B^k$ denotes all causal paths of all lengths in the system, including diverging, converging and feedback paths. This is the transitive closure property, meaning that all causality propagated within the system network is accounted for. B^* is a transitive closure matrix. This matrix for the marine coprophagy model is the last of the set that appears in table 2.

Leontief (1936) developed a method for steady state analysis of economic systems that requires the transitive closure property. The procedure, as modified and extended by Finn (1976), in effect defines within system input and output environments of each component level holon. The more complicated nonsteady state case is discussed in Patten *et al* (1976).

Referring to figure 2, let: (1) H_i and H_j represent subsystem level components

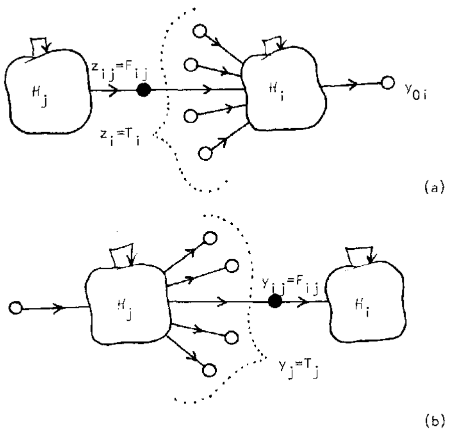

FIGURE 2. Derivation of transitive closure input and output matrices, $(I-Q')^{-1}$ and $(I-Q'')^{-1}$, respectively. (a) Creaon case; (b) genon case.

of an n component system H when $i, j=1, \ldots, n$; (2) H_j denote system input environment H' when $j=0$; and (3) H_i be system output environment H'' when $i=0$. Input from H' to H_j ($j=1, \ldots, n$) is z_{j0}, and output to H'' from H_i is y_{0i}. In figure 2a, if output y_{0i} is received or perceived from H_i by some observer, then the input environment H_i' required to produce y_{0i} is of interest. Reciprocally, in figure 2b the environment H_j'' of influence generated in response to z_{j0} is the concern.

In deriving these environments it is convenient to introduce two sets of identity constraints.

(1) *Interaction constraints:* $z_{ij} \equiv y_{ij} = F_{ij}$, $i, j=0, \ldots, n$.

(2) *Steady state constraints:* $z_i \equiv y_i = T_i$, $i=1, \ldots, n$

The first identities allow a direct causal *flux* F_{ij} from H_j to H_i to be recognized without distinguishing whether it is an input z_{ij} to H_i from H_j (fig. 2a) or an output y_{ij} from H_j to H_i (fig. 2b). The second constraints make it possible to recognize the total *throughput* T_i of H_i without considering whether it corresponds to total input (fig. 2a) or total output (fig. 2b) from the holon in question. Intrasystem environments of component level holons may now be derived.

CREAON CASE

In figure 2a, let total output y_j from H_j be

(3) $$y_j = \sum_{i=0}^{n} y_{ij},\ j=1,\ldots,n,$$

where i=0 denotes output to H''. This latter output y_{0j} to the sysem's environment can be isolated:

(4) $$y_j = \sum_{i=1}^{n} y_{ij}+y_{0j},\ j=1,\ldots,n;$$

it is illustrated as y_{0i} for H_i in figure 2a. Applying constraints (1) and (2), the last expression (4) can be rewritten

(5) $$T_j = \sum_{i=1}^{n} F_{ij}+y_{0j},\ j=1,\ldots,n.$$

The direct cause F_{ij} from H_j to H_i can be expressed as a fraction of the throughput T_i of H_i:

(6) $F_{ij}=q'_{ij}T_i$, i, j=1, . . . , n,

which, substituted into (5), gives

(7) $$T_j = \sum_{i=1}^{n} q'_{ij}T_i+y_{0j},\ j=1,\ldots,n.$$

In matrix notation this becomes

(8) $\underset{\sim}{\mathbf{T}}=\underset{\sim}{\mathbf{T}}Q'+,\underset{\sim}{\mathbf{y}}$

where $\underset{\sim}{\mathbf{T}}$ is a 2n-dimensional vector of the n holon throughputs T_j, $\underset{\sim}{\mathbf{y}}$ is a 2n-dimensional vector of holon outputs to H'', and Q' is a 2n x 2n matrix of fractional direct causes q'_{ij} from H_j to H_i per unit of throughput T_i [eq. (4)]. The output vector $\underset{\sim}{\mathbf{y}}$ and throughput vector $\underset{\sim}{\mathbf{T}}$ are incated in table 1 for the marine coprophagy model. The Q' matrix for this model is shown in table 3a. Correspondence of the intrasystem submatrix with the Boolean matrix B in table 2 should be noted. Equation (6) can be solved for $\underset{\sim}{\mathbf{T}}$:

(9) $\underset{\sim}{\mathbf{T}}(I-Q')=\underset{\sim}{\mathbf{y}}$

$\underset{\sim}{\mathbf{T}}=\underset{\sim}{\mathbf{y}}(I-Q')^{-1}$

where

(10) $(I-Q')_{ij}^{-1}=\phi_{ij}/y_{0i}$, i, j=1, . . . , n.

Here, ϕ_{ij} represents the total causal flux (direct, F_{ij}, plus indirect) from H_j to H_i overall possible pathways of propagation

TABLE 3

(A) Fractional input matrix Q' and (B) fractional output matrix Q'' for the marine coprophagy model.

(A) H_i \ H_j	from x_1	x_2	x_3	x_4	z_{10}	z_{20}	z_{30}	z_{40}
x_1	0	0	0	0	1.0	0	0	0
x_2	1.0	0	0	0	0	0	0	0
x_3	0	0.047	0	0.163	0	0	0.789	0
x_4	0	0	1.0	0	0	0	0	0
to— z_{10}	0	0	0	0	0	0	0	0
z_{20}	0	0	0	0	0	0	0	0
z_{30}	0	0	0	0	0	0	0	0
z_{40}	0	0	0	0	0	0	0	0

(B) H_i \ H_j	from x_1	x_2	x_3	x_4	y_{01}	y_{02}	y_{03}	y_{04}
x_1	0	0	0	0	0	0	0	0
x_2	0.176	0	0	0	0	0	0	0
x_3	0	0.700	0	0.664	0	0	0	0
x_4	0	0	0.246	0	0	0	0	0
to— y_{01}	0.824	0	0	0	0	0	0	0
y_{02}	0	0.300	0	0	0	0	0	0
y_{03}	0	0	0.754	0	0	0	0	0
y_{04}	0	0	0	0.336	0	0	0	0

through the interconnection network of H, and $(I-Q')_{ij}^{-1}$ represents the amount of this flux normalized to one unit of output y_{0i} observed from H_i (fig. 2a). Thus, the matrix $(I-Q')^{-1}$ must be a transitive closure matrix, and conditions to guarantee this are to be established. The input environment defining $(I-Q')^{-1}$ matrix for the marine coprophagy model is depicted in table 4a.

Just as entries in Q' represent direct causal links of length 1, $(Q')^2$ denotes causality propagated indirectly over paths of length 2, $(Q')^3$ over length 3 paths, and in general $(Q')^k$ over paths of length k. From the identity

(11) $(I+Q+Q^2+\ldots)(I-Q)=I,$

it follows that

(12) $$\lim_{\ell\to\infty}\sum_{k=0}^{\ell}(Q')^k=(I-Q')^{-1}$$

if the limit exists. For the series to converge, $(Q')^k\to 0$ as $k\to\infty$; that is, all causal paths of all lengths must be accounted for. If this (transitive closure) occurs, the convergence is to an inverse matrix of the form $(I-Q')^{-1}$. Such matrices are therefore transitive closure matrices, provided the limit exists.

Existence conditions are well known in linear algebra (e.g., Faddeev and Faddeeva 1963). Ortega (1972), cited by Hannon (1973), gives the following convergence theorem. Block diagonalize Q',

(13) $$Q'=\begin{Bmatrix} Q_1' & 0 & \cdot & \cdot & \cdot & 0 \\ 0 & Q_2' & \cdot & \cdot & \cdot & 0 \\ \cdot & & \cdot & \cdot & & \cdot \\ \cdot & & \cdot & & \cdot & \cdot \\ \cdot & & \cdot & & \cdot & \cdot \\ 0 & 0 & \cdot & \cdot & \cdot & Q_m' \end{Bmatrix},$$

forming m irreducible block diagonal submatrices such that $\det Q_1' \cdot \det Q_2' \cdot \ldots \cdot \det Q_m' = \det Q'$. In each block submatrix sum the state variable entries in each state variable row. $(I-Q')^{-1}$ exists if and only if for each block submatrix the sum of state variables in each row is strictly <1 for at least one state variable row. The significance is that at least one component level holon in

TABLE 4

(A) Transitive closure input environment matrix $(I-Q')^{-1}$ and (B) output environment matrix $(I-Q'')^{-1}$ for the marine coprophagy model.

(A) H_i \ H_j	from: x_1	x_2	x_3	x_4	z_{10}	z_{20}	z_{30}	z_{40}
to— x_1	1.0	0	0	0	1.0	0	0	0
x_2	1.0	1.0	0	0	1.0	0	0	0
x_3	0.057	0.057	1.195	0.195	0.057	0	0.943	0
x_4	0.057	0.057	1.195	1.195	0.057	0	0.943	0
z_{10}	0	0	0	0	1.0	0	0	0
z_{20}	0	0	0	0	0	0	0	0
z_{30}	0	0	0	0	0	0	1.0	0
z_{40}	0	0	0	0	0	0	0	0

(B) H_i \ H_j	from: x_1	x_2	x_3	x_4	y_{01}	y_{02}	y_{03}	y_{04}
to— x_1	1.0	0	0	0	0	0	0	0
x_2	0.177	1.0	0	0	0	0	0	0
x_3	0.148	0.837	1.195	0.794	0	0	0	0
x_4	0.036	0.206	0.294	1.195	0	0	0	0
y_{01}	0.824	0	0	0	1.0	0	0	0
y_{02}	0.053	0.300	0	0	0	1.0	0	0
y_{03}	0.111	0.631	0.901	0.598	0	0	1.0	0
y_{04}	0.012	0.069	0.099	0.402	0	0	0	1.0

TABLE 5

Block diagonal forms of (A) creaon matrix Q' (table 3a) and (B) genon matrix Q" (table 3b) for the marine coprophagy model.

(A) H_j / H_1		*from* z_{10}	z_{20}	x_1	z_{30}	z_{40}	x_2	x_4	x_3	state variables row Σ
to	x_1	1.0*	0	0	0	0	0	0	0	0
	x_2	0	0	1.0	0	0	0	0	0	1.0
	z_{10}	0	0	0	0	0	0	0	0	—
	x_3	0	0	0	0.789*	0	0.047	0.163	0	0.2
	x_4	0	0	0	0	0	0	0	1.0	1.0
	z_{20}	0	0	0	0	0	0	0	0	—
	z_{30}	0	0	0	0	0	0	0	0	—
	z_{40}	0	0	0	0	0	0	0	0	—

(B) H_j / H_i		*from* x_1	y_{01}	x_2	x_4	y_{02}	x_3	y_{03}	y_{04}
	y_{01}	0.824*	0	0	0	0	0	0	0
	x_2	0.176	0	0	0	0	0	0	0
	y_{02}	0	0	0.300*	0	0	0	0	0
to	x_3	0	0	0.700	0.664	0	0	0	0
	y_4	0	0	0	0.336*	0	0	0	0
	x_4	0	0	0	0	0	0.246	0	0
	y_{03}	0	0	0	0	0	0.754*	0	0
	x_1	0	0	0	0	0	0	0	0
state variables column Σ		0.176	—	0.700	0.664	—	0.246	—	—

*See text below.

each submatrix must have input contact with the system's input environment H', and that this must be true for all of the m subsystems formed by the matrix diagonalization procedure. Thus, to account for all causal propagation within a system H, it is necessary to refer to an environment H' outside of H. This is Proposition 2, for the creaon case.

Block diagonalization of Q' for the marine coprophagy model is illustrated in table 5a. Row sums appear in the right hand column. For both Q_1' and Q_2' the sum of state variable rows is <1 for at least one such row, namely the row for x_1 in Q_1' due to input z_{10} to H_1 (indicated by an asterisk), and the row for x_3 in Q_2' due to input z_{30} to H_3 (asterisk). Existence of the transitive closure matrix $(I-Q')^{-1}$ for this model is thus established, and the matrix in fact is illustrated in table 4a. The input environments H_1', . . . , H_4' that it defines will be clarified later.

GENON CASE

A parallel development is required to establish Proposition 2 with respect to output environment. In figure 2b, let the total input z_i to H_i be

$$(14)\quad z_i = \sum_{j=1}^{n} z_{ij} + z_{i0},\ i=1, \ldots, n,$$

where z_{i0} (fig. 2b) is input from the system level environment H'. Applying equations (1) and (2) as before gives

$$(15)\quad T_i = \sum_{j=1}^{n} F_{ij} + z_{i0},\ i=1, \ldots, n.$$

F_{ij} can be expressed as a fraction of the throughput T_j of H_j:

$$(16)\quad F_{ij} = q''_{ij} T_j,\ i, j=1, \ldots, n,$$

which, substituted into (15), results in

$$(17)\quad T_i = \sum_{j=1}^{n} q''_{ij}T_j + z_{i0},\ i = 1, \ldots, n.$$

In matrix notation this becomes

$$(18)\quad \underset{\sim}{\mathbf{T}} = Q'' \underset{\sim}{\mathbf{T}} + \underset{\sim}{\mathbf{z}},$$

where $\underset{\sim}{\mathbf{T}}$ is a 2n-dimensional throughput vector, $\underset{\sim}{\mathbf{z}}$ is a 2n-dimensional vector representing inputs from H', and Q'' is a 2n x 2n matrix of fractional direct effects) q_{ij}'' from H_j to H_i per unit of T_j [eq. 16c]. Input $\underset{\sim}{\mathbf{z}}$ and throughput $\underset{\sim}{\mathbf{T}}$ vectors for the marine coprophagy model are indicated in table 1. Table 3b shows the Q'' matrix. Solving eq. (18) for $\underset{\sim}{\mathbf{T}}$:

$$(19)\quad (I-Q'')\underset{\sim}{\mathbf{T}} = \underset{\sim}{\mathbf{z}}$$
$$\underset{\sim}{\mathbf{T}} = (I-Q'')^{-1}\underset{\sim}{\mathbf{z}},$$

where

$$(20)\quad (I-Q'')_{ij}^{-1} = \phi_{ij}/z_{j0},\ i, j = 1, \ldots, n.$$

ϕ_{ij} is the total (direct, F_{ij}, plus indirect) effect of H_j on H_i transmitted over all possible paths interconnecting the components of H. $(I-Q'')_{ij}^{-1}$ is the same total effect normalized to a unit of input z_{j0} to H_j (fig. 2b). Therefore, $(I-Q'')^{-1}$ requires the transitive closure property, for which conditions must be established. This output environment defining matrix for the marine coprophagy model appears in table 4b.

As before, Q'' denotes direct effects and $(Q'')^k$ indirect effects over paths of length k. From identity (11), series convergence is to an inverse matrix,

$$(21)\quad \lim_{\ell\to\infty} \sum_{k=0}^{\ell} (Q'')^k = (I-Q''),^{-1}$$

if the limit exists. Again, diagonalize Q'' into m irreducible block submatrices satisfying $\det Q_1'' \cdot \det Q_2'' \ldots \cdot \det Q_m''$. In each block submatrix sum the state variable entries in each state variable column. $(I-Q'')^{-1}$ exists if and only if for each submatrix the sum of state variables in each column is strictly <1 for at least one state variable column. That is, at least one holon in each subsystem represented by a block diagonal matrix must have output contact with the output environment H'' of H; no subsystem so defined may lack such contact. Hence, to account for all propagation of effects within a system H it is necessary to reference, as output, an environmental system H'' external to H. This is Proposition 2 expressed for the genon case.

Block diagonalization of Q'' for the marine coprophagy model is shown in table 5b. Column sums appear in the bottom row. For submatrix Q_1'' the sum of the only state variable column, x_1, is <1 due to out put y_{01} form H_1 (shown by *). In Q_2'' both state variable column sums are <1 because H_2 and H_4 both generate output to H'' (asterisks). And in Q_3'', column x_3 sums to <1 because of output y_{03} from H_3 (asterisk). The existence condition for $(I-Q'')^{-1}$ is met for this model, and the matrix is shown in table 4b. The output environments $H_1'', \ldots, H_4''$ defined by this matrix will be demonstrated in the next section.

The second proposition has been established. The internal interactive structure of systems cannot be fully specified, with all causal pathways of all lengths accounted for, without reference to an exogenous input or output environment, or both. The systems must be open systems. The causal pattern within closed systems cannot be completely specified, from which it may be concluded that it is a function of environments to validate the internal nature of their defining systems.

As Patten *et al* (1976) indicate, Proposition 2 can also be realized from Markov chain theory. Its ultimate generality, however, is probably conferred by the fact that it may be a manifestation of Gödel's famous theorem (e.g., Nagel and Newman 1956) on incompleteness of logical systems. Gödel in what is considered one of the mathematical landmarks of this century, showed that the consistency of any deductive system cannot be established without reference to some external system of logic whose own consistency is in question without reference to a further external system, etc. If logical systems have logical "environments" which must be consulted to demonstrate internal consistency of the former, then it should be no surprise that nature as comprehended by the same mind that created logic should possess the same characteristic inherent in the object/environment relationship.

Propositions 1 and 2 together signify that the object (organism)/environment pair is an inseparable, mutually defining unit. In the next section, a system is formulated as a composition of such subsystem level units.

THIRD PROPOSITION

Proposition 3: A system can be constructed as a set union of mutually disjoint and exhaustive object/environment elements (environs). The within system object/environment units of Propositions 1 and 2 form a partition at the system level of organization.

This final proposition can be illustrated advantageously with the marine co-prophagy model. First, the formal statement. Let H_i, $i=1, \ldots, n$, be a subsystem level component of an n-component system H, with input environment H' and output environment H'' at the supersystem level. The within system input environment of H_i is H_i', and the corresponding output environment is H_i''. The creaon/input environment and genon/output environment units have been well enough established by Propositions 1 and 2 that they can be regarded as entities in their own right. They will be termed input and output *environs* (within system object/environment units), E_i' and E_i'' respectively, $i=1, \ldots, n$. This is consistent with normal usage in which the word environ refers ot nearby surroundings. Here, nearby means within the boundary of the defined system. Proposition 3 can be formulated in terms of these units: input environs do not overlap,

(22) $E_i' \cap E_j' = \phi$, i, j = 1, . . . , n,

ϕ the empty set; output environs also are nonintersecting,

(23) $E_i'' \cap E_j'' = \phi$, i, j = 1, . . . , n;

and system H is a union of input or output environs,

$$(24) \quad H = \bigcup_{i=1}^{n} E_i' = \bigcup_{i=1}^{n} E_i''.$$

The sense of these statements will now be clarified.

Table 4a shows the $(I-Q')^{-1}$ transitive closure matrix for the marine coprophagy model. This matrix defines the input environs E_i' of this model normalized to one unit of output y_{0i} from each component holon H_i ($i=1, \ldots, 4$). These normalized input environs are depicted in figure 3. Each environ is relative to a unit output (heavy arrows) from the component holons. Numbers within the holon symbols denote throughputs required to generate the unit outputs; numbers associated with arrows represent propagated causes that sum to the throughputs. Correspondences between figure 3 and table 4a are obvious. To express the normalized environs as carbon flows (gC m^{-2} y^{-1}) numbers in the figure and table must be multiplied by the corresponding output flux as given in figure 1. The normalized versions (fig. 3) will be used for interpretation.

Consider E_4' in figure 3. Observation (measurement) of one unit of carbon output from H_4 specifies the indicated causal network as input environment H_4'. Causation is traced back through the network to its origins at the system boundary. Most of the output from H_4 derives from input to H_3 (94.3%), and only a small amount (5.7%) originates with H_1 input. The relations shown for the remaining three input environs are self evident. If these four normalized environs $E_1', \ldots, E_4'$ are scaled to actual carbon flows and summed, the original figure 1 system is reconstructed. That is,

$$(25) \quad H = \sum_{i=1}^{4} E_i'.$$

Thus, the input environs of figure 3 are nonintersecting [eq. (22)] and also exhaustive [eq. (24)], establishing Proposition 3 for the creaon case.

Table 4b presents the $(I-Q'')^{-1}$ matrix for the marine coprophagy model. This matrix defines output environs E_j'' normalized to one unit of input z_{j0} to each component holon H_j ($j=1, \ldots, 4$). These normalized environs are depicted in figure 4, each in relation to a unit input (heavy arrows) to the member holons. Numbers within holon symbols denote throughputs generated by the unit inputs, and numbers associated with arrows indicate propagated effects which sum to the throughputs. To express the environs in terms of absolute carbon flows, figure 4 values should be multiplied by the associated inputs in gC m^{-2} y^{-1} as given in

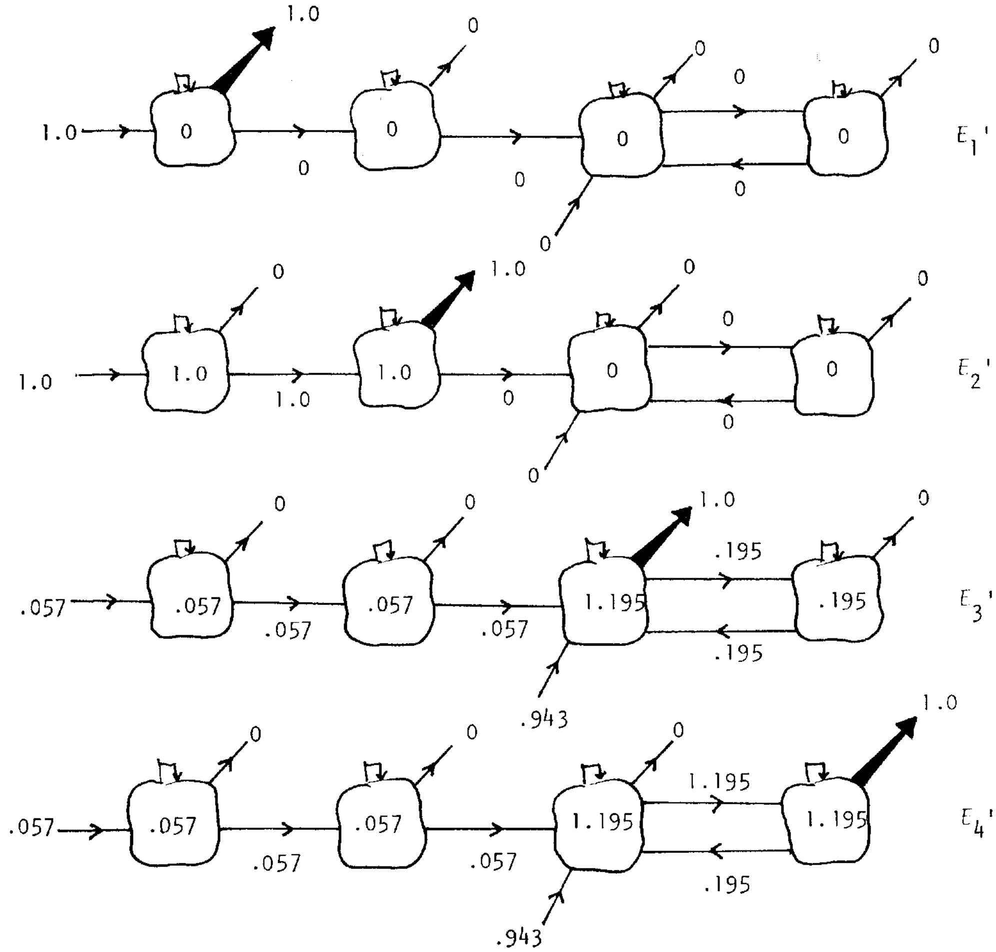

FIGURE 3. Normalized input environs E_1', . . . , E_4' which partition the steady state marine coprophagy model.

figure 1. The normalized environs (fig. 4) will again be interpreted.

In the upper diagram of figure 4 depicting E_1'', 82.4% of H_1 input exits the system at H_1, 5.3% at H_2, 11.1% at H_3 and 1.2% at H_4. The within system propagated effects leading to these outputs are shown. The other environs provide similar information about the fate of other inputs. If these environs are dimensionalized to actual carbon flows (gC m^{-2} y^{-1}) and the results summed, the original figure 1 system is again recomposed. That is,

$$H = \sum_{j=1}^{4} E_j'', \tag{26}$$

indicating that the output environs E_1'', . . . , E_4'' are mutually exclusive [eq. (23)] and exhaustive [eq. (24)]. Proposition 3 is therefore established for the genon case.

Thus, for general systems, but especially for ecosystems which motivate this theory, within system object (organism)/environment units (environs) form set partitions at the system hierarchical level. Two such partitions are possible, one by input environs and the other by output environs. Both are distinct and different as the input and output environs defined by a given holon are distinct and different ($E_i' \neq E_i''$, i = 1, . . . , n). von Uexküll (1926) apparently appreciated the disjoint property of such partitions when he wrote, "For each individual animal, . . . its function-circles constitute a world by themselves, within which it leads its existence in complete isolation."

DISCUSSION

Ecology was stated previously in this paper to take a fundamentally physiological view of environment. This is consistent with ordinary usage in which living or nonliving systems are influenced by external surroundings. The physiological concept is manifested in Mason and Langenheim's (1957) theory, which limits environment to direct causes only. This is the normal ecological view of environment, although other viewpoints (e.g., Haskell 1940) have been offered. The systems concept outlined above differs from the normal one in four particular ways: two environments are recognized instead of one; indirect causality is included; the object (organism)/environment complex is unitary; and the units (environs) partition reality.

TWO ENVIRONMENTS

The causal holon H is a general systems object that originates not one, but two, environments, H' (input) and H'' (output). If H is a system level object, H' and H'' are supersystem concepts and cannot be further described. If H is a subsystem, then its within system environments can be specified to the

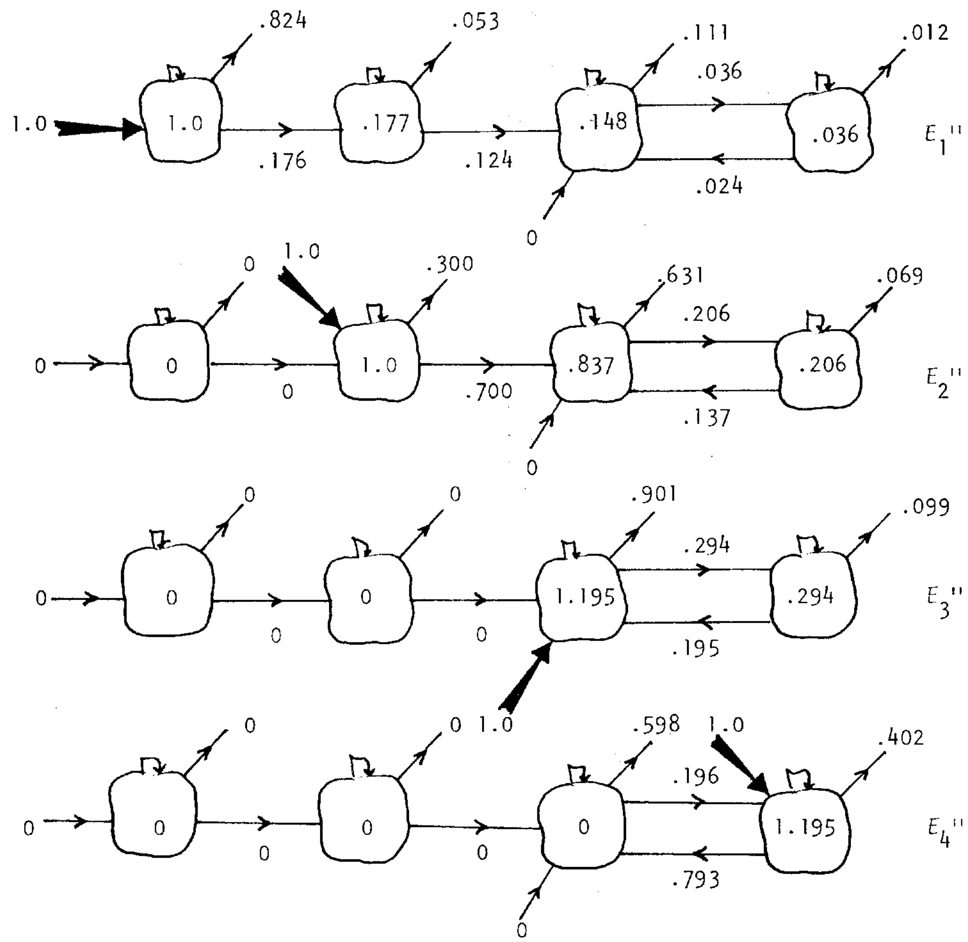

FIGURE 4. Normalized output environs E_1'', . . . , E_4'' which partition the steady state marine coprophagy model.

system boundary as input and output environs, E' and E'', respectively. The environ is a new class of object in system theory. What it may contribute to the understanding of ecological or general systems remains to be seen. For example, where a holon is a biological object, inheritance and evolution of its environs may be reasonable to consider as outward projections of known genetic mechanisms. The necessity for objects to interact consistently within environs provides constraints that almost certainly guarantee coevolution to be an ecosystem level phenomenon (Patten *et al* 1976; Patten 1977). Prospects for an organismic representation of environment are quite real in this theory.

The normal one-environment concept includes only input environment. von Uexküll (1926) provided a precedent for output environment in the notion of function circles that fail of closure (output affecting input) due to complexity of the external world. Propagated effects become lost in the general flux of causation before they can return as identifiable inputs to the original generating organism. By explicitly recognizing two environments, an analytical potential is gained that is absent in a one-sided theory. Creaon and ģenon partitions (eg., figs. 3 and 4) are never the same, and patterns of how they differ are foreseeable system properties of interest. For example, Patten (1978) has analyzed control relationships in ecosystem models by comparing input and output environs of component holons.

INDIRECT CAUSALITY

Mason and Langenheim (1957) wrote that to include indirect factors in environment is to confuse environment with history. In the two-environment approach the future enters as a similar objection. How should time be regarded in a concept of environment? Two aspects of the question are dynamic and static.

Let H be a component of a system that exists with respect to a cause during $[t', t'']$, $t' \leq t \leq t''$, $t \epsilon T$. (Symbols [,], (and) mean $\geq$, $\leq$, $>$ and $<$, respectively, in denoting time intervals.) t' is the time the cause initially enters the system as input, t is present time, and t'' is the time at which a corresponding effect is generated as system output. Dynamically, H defines its input and output environments H' and H'' instantaneously at time t through direct interactive coupling to other holons of the system. In input environs E', indirect causality, which conditions the direct coupling events at t, has already occurred during the past $[t', t]$. Thus, an instantaneous input environ defined at t encompasses a historical network of causation extending backward to the system boundary at t'. Similarly, indirect effects in an instantaneous output environ E'' are propagated from the direct coupling events at time t during the future, $[t, t'']$. The instantaneous output environ contains the succession of indirect causes and effects extending forward to the system boundary at t''. Note that the system exists with respect to a cause introduced at t' only during the interval $[t', t'']$ required for it to generate a corresponding effect at t'', and this is true $\forall t', t'' \epsilon T$. The role of holon H in the system relative to the same cause is similarly restricted to the same interval. Without a temporally finite model Mason and Langenheim's (1957) objection of infinite regress, and a counterpart infinite future progression of the two-environment theory, would be valid. So long as a holon's memory of the past and horizon to the future are relatively small, so that its system appears relatively permanent compared to itself, this permanent organization should be represented in its environs. Environment as a concept is not instantaneous. It is *natural history*, a window on the relatively near past and future, and to make it so, indirect causality must be included. Therefore, instantaneous input environs E' defined at time t properly span intervals $[t', t]$, and corresponding output environs E'' span intervals $[t, t'']$.

The static case reflects this. Static models depict, usually, steady state characteristics of systems over time spans that are long compared to the time scales of dynamic properties. For example, the marine coprophagy model of figure 1 represents a persistent steady state organization expressed as mean annual carbon storages and flows. Finer time resolution is not desired, and no time difference is implied between inputs and outputs. Each static environ (figs. 3 and 4) represents average relationships inherent in the system organization year after year. Historical aspects are suppressed in such static abstractions. This obscures the fact that the commonsense concept of environment is actually a systems concept. It includes indirect causation implicitly, because in its stasis it presumes relatively constant ecological organization over relatively long time scales.

To illustrate, the immediate physical and informational environment of my office here as I write is not the environment of concern when I consider environmental management or protection. This local direct environment is well managed by lights, windows and thermostats. To continue to guarantee these devices and my personal well-being, without which they would be meaningless, I must and do consider phenomena at the far reaches of my environs that never will touch this office directly. DDT, mercury, radioactivity or a thousand other hazards and other aspects may or may not ever directly impinge on me, but they already affect me and my management of this place. This knowledge is implicit in my working approach to environment, based on a static model in my mind of both direct and indirect factors. Man as a species (i.e., as an aggregate holon defining aggregate input and output environs) takes account of indirect factors habitually. Only recently, with the advent of computers, has this systems reflex begun to be implemented in non-static models. Indirect causality is an integral part of environment, and in both dynamic and static cases is correctly included in the systems approach to the concept.

HOLON/ENVIRONMENT UNITY

In Proposition 1 a holon defines a pair of environments, and in Proposition 2 these environments confer completeness upon the holon's internal organization. Input and output environments may be considered outward extensions of physical, chemical or biological characteristics of the holon's inner organization, mechanism and law. The holon similarly may be regarded as an inward projection of the properties of its environments, the creaon a reflection of input environment and the genon a reflection of output environment. An unbroken continuum of causes and effects streams across the holon/environment boundary. Propositions 1 and 2, with probable support from Gödel's theorem (Nagel and Newman 1956), strongly portray the holon/environment complex as a unit.

The nature of the relationship between a defining holon and other holons with which it interacts only indirectly contributes to a unified concept. Consider the input environ E_4' illustrated at the bottom of figure 3. H_4 takes account of H_3 by direct interactive coupling, but can never have a similar relation to H_2 or H_1, with which it is only indirectly connected in the model. In the dynamic case, H_1 or H_2 may both have gone out of existence by the time H_4 receives carbon that they processed. What then can be said of the relation, if any, of H_4 to H_1 and H_2? Similarly, for the genon case refer to output environ E_1'' depicted at the top of figure 4. Coupling of H_1 to H_2 is direct but H_1 is only indirectly related to H_3 and H_4. Dynamically, H_1 may no longer exist by the time its generated effects are propagated to H_3 and H_4. What is the environmental relation, if any, of H_1 to H_3 and H_4? The defining holon of an input or output environ is influenced by or influences all member holons in the environ. The defining holon becomes, in effect, a synthesis of its relations to all direct and indirect phenomena which condition it (creaon) or which it conditions (genon). Thus, a holon and its environments are properly considered as units, as expressed in the environ concept.

ENVIRON PARTITIONS

A special feature of the present theory not shared with conventional concepts of environment is system partition according to Proposition 3. As indicated before, von Uexküll (1926) held that organisms live isolated within the world of their own function circles. The same idea appears here in the form of holons relating only to things in their own environs. The sense in both cases is not that entities in nature do not interact, but that the transactions and communications (energy-matter and information exchanges, respectively) by which they do so are unique. If environs of different holons are disjoint, they also may be dissimilar even if the same physical phenomena are represented. A real entity depicted in an environ of H_i may have a different character and significance when represented in an environ of H_j. An environ is then an abstraction formed by its defining holon—a representation or model of that holon's separate reality. Presumably, it is refined and improved in some evolutionary synthesis appropriate to the holon's physical, or biological nature and level of organization.

How these disjoint models combine to exhaust the concrete reality which is nature is for philosophers, and not ecologists, to understand.

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